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Mineral resources in life cycle impact assessment—part I: a critical review of existing methods

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41 Abstract

42 Purpose

The safeguard subject of the Area of Protection "Natural Resources", particularly regarding mineral resources, has long been debated. Consequently, a variety of Life Cycle Impact Assessment methods based on different concepts are available. The Life Cycle Initiative, hosted by UN Environment, established an expert task force on "Mineral Resources" to review existing methods (this article) and provide guidance for application-dependent use of the methods, and recommendations for further methodological development (Berger et al., 2019).

49 Methods

50 Starting in 2017, the task force developed a white paper, which served as its main input to a SETAC 51 Pellston Workshop® in June 2018, in which a sub-group of the task force members developed 52 recommendations for assessing impacts of mineral resource use in LCA. This article, based mainly on 53 the white paper and pre-workshop discussions, presents a thorough review of 27 different Life Cycle 54 Impact Assessment methods for mineral resource use in the "Natural Resources" Area of Protection. 55 The methods are categorized according to their basic impact mechanisms, described and compared, 56 and assessed against a comprehensive set of criteria.

57 Results and discussion

58 Four method categories have been identified and their underlying concepts are described based on

59 existing literature: Depletion methods, Future Efforts methods, Thermodynamic Accounting methods,

and Supply Risk methods. While we consider Depletion and Future Efforts methods more "traditional"

61 Life Cycle Impact Assessment methods, Thermodynamic Accounting and Supply Risk methods are

rather providing complementary information. Within each method category, differences between
methods are discussed in detail, which allows for further sub-categorization and better understanding
of what the methods actually assess.

65 Conclusions

We provide a thorough review of existing Life Cycle Impact Assessment methods addressing impacts of mineral resource use, covering a broad overview of basic impact mechanisms to a detailed discussion of method-specific modeling. This supports a better understanding of what the methods actually assess, and highlights their strengths and limitations. Building on these insights, Berger et al. (2019) provide recommendations for application-dependent use of the methods, along with recommendations for further methodological development.

72

- 73 Keywords: Life Cycle Assessment, Life Cycle Impact Assessment, method review, mineral resources,
- raw materials, resource depletion, Life Cycle Initiative, Task Force Mineral Resources

76 1 Introduction

77 Mineral resources – defined here as chemical elements (e.g. copper), minerals (e.g. gypsum), and 78 aggregates (e.g. sand) as embedded in a natural or anthropogenic stock - are of great relevance for 79 industry and society. Environmental impacts associated with mineral resource extraction are assessed 80 in relatively well-established Life Cycle Impact Assessment (LCIA) categories, e.g., climate change or 81 acidification (see e.g. Nuss and Eckelman 2014). However, how to assess other impacts of mineral 82 resource use as such -e.g. whether in terms of the availability of these resources for future generations 83 or in terms of shorter-term risks of supply-chain disruptions – has been a subject of persistent debate 84 (see e.g. Dewulf et al. 2015; Drielsma et al. 2016b) and a variety of LCIA methods based on different 85 concepts are available (see e.g. Sonderegger et al. 2017). It is still discussed what the safeguard subject of the Area of Protection (AoP) "Natural Resources" should be (Sonderegger et al. 2017; Berger et al. 86 87 2019). It is even questioned whether an impact assessment of mineral resource use - that by definition 88 comprises environmental and economic aspects – is in the scope of an environmental LCA at all 89 (Drielsma et al. 2016b). It might be due to the ambiguity on what actually should be protected with 90 regard to mineral resources in LCA that various impact pathways are currently modeled, assessing 91 different consequences of mineral resource use, e.g. the depletion of reserves, increased efforts for 92 future extraction, or short-term supply risks. Furthermore, often inadequate methods are applied in 93 LCA practice, providing the "right" answer to the "wrong" question: e.g. methods assessing the long-94 term depletion of mineral resources in the Earth's crust are mistakenly used by LCA practitioners who 95 are actually interested in the short-term economic risks of raw material supply disruptions (Fraunhofer 96 2018).

97 To address these challenges, the Life Cycle Initiative, hosted by UN Environment, established an 98 expert task force on "Mineral Resources" within its broader project on "Global Guidance for LCIA 99 Indicators". The output of the task force is presented in this review of existing methods, which also 100 served as basis for a recommendations paper (Berger et al. 2019). This review paper describes the task 101 force and its working process, gives an overview of reviewed methods and their impact mechanisms, 102 categorizes and describes the methods in detail, assesses them based on an assessment scheme, and 103 finally discusses their strengths and limitations. The aim is to describe and compare methods with 104 regard to their methodological approaches in order to better understand what the methods actually 105 assess.

106 2 The task force

107 The task force comprised 62 members from academia, the metals and mining industry, other 108 industries, geological departments, consulting, and Life Cycle Inventory (LCI) database providers, 109 representing 14 countries around the globe. 23 members (17 from academia, amongst them many 110 method developers, 4 from consulting, 1 from the metals and mining industry, 1 from oil and gas 111 industry) have been "active" members, participating in calls, working in sub-groups, and finally contributing to the scientific publications. The task force commenced in the beginning of 2017. Based 112 113 on discussions in regular online meetings, the task force developed a white paper, which served as the 114 main input to a SETAC Pellston Workshop® in June 2018. In this workshop, a sub-group of 8 of the task force members with complementary backgrounds and expertise (5 from academia, 2 from 115 consulting, 1 from oil and gas industry) agreed on recommendations. This review paper is mainly 116 117 based on the white paper and the pre-workshop discussions whereas the recommendations paper 118 (Berger et al. 2019) mainly presents the workshop discussions and output.

119 3 Material flow and impact mechanisms overview

120 At the time the task force started its work, 27 different methodological approaches 33 methods assessing impacts of mineral resource use were available from literature or provided to the task force 121 122 internally by method developers. For those methods with methodological differences between an old 123 and an updated version, e.g. Anthropogenic Stock Extended Abiotic Depletion Potential method (AADP) or EDIP, we reviewed both in order to cover all the different approaches. For the other 124 125 methods, we only considered the most recent version, e.g. LIME. This resulted in a set of 27 different 126 methodological approaches. We first identified their basic impact mechanisms and related these to 127 flows of mineral resources from the lithosphere through the technosphere and finally back into the 128 ecosphere (Figure 1).



Figure 1: Material flow (grey layer) and impact mechanisms overview, presented in color for Depletion methods (green),
Future Effort methods (yellow), Thermodynamic Accounting methods (orange), Supply Risk methods (blue), and the
"Dilution of total stocks" approach (purple). Dashed material flows and impact pathways are proposed or discussed but not
agreed, operational, or published yet.

135 The material flow layer (grey layer in Figure 1) shows that primary/natural mineral resources are 136 extracted from natural stocks in the lithosphere (a part of the ecosphere) and enter the technosphere via 137 mining and quarrying, further on just called mining. Mineral resources are immobilized in products and infrastructure (collectively termed "in-use stocks") for short to long time scales (e.g. aluminium 138 can vs. steel bridge) and at different qualities. By means of recycling, mineral resources can be kept 139 and cycled inside the technosphere for different time scales and at different qualities (up- or down-140 cycling). If products are not recycled, mineral resources can be stored at different qualities in disposal 141 stocks, e.g. landfill stocks, from which they potentially may be recovered. The quality of an abiotic 142 resource may be a complex composite of different quality aspects. With regard to the efforts needed to 143 144 extract a resource from a natural mineral deposit, this might for example include target element grade, "gangue minerals" or impurity grades, grain size distributions and grain "texture", ore hardness, size 145 146 and heterogeneity of the deposit, or accessibility (e.g. depth, remoteness). Conceptually many of these aspects may be applicable to extraction from anthropogenic stocks with some tweaking. The 147 148 anthropogenic stock in the technosphere (product + disposal stocks) is the source for secondary/anthropogenic mineral resources. Therefore, it is argued that an actual loss of mineral 149 150 resources for human use only occurs through dissipation, i.e. any form of use rendering a mineral

resource unrecoverable, whether in the ecosphere or in the technosphere. For further discussion of the dissipation concept, see Berger et al. (2019). Supplementary <u>material-Material</u> 1 (section S2) further describes and details mineral resource quality, dissipation, and the ecosphere-technosphere boundaries.

154 On top of the material flow layer, an impact mechanism layer (coloured layer in Figure 1) has been 155 added to show the position of characterization models in the material flow context. Starting from mineral resource extraction, some methods model the depletion of natural stocks (in one case also 156 157 considering the anthropogenic stock) (in green), others the extraction of exergy (i.e. the exergy 158 difference between the mineral resource as found in nature and a defined reference state in the natural environment) (in orange), and still others an ore grade decline and resulting additional ore 159 160 requirements, energy, or costs (in yellow). Other methods do not consider physical parameters but 161 directly model economic externalities, i.e. costs or welfare loss for future generations (also yellow). 162 Another category of methods (in blue) model the supply risk of mineral resources/raw materials in the 163 technosphere, taking into account the probability of supply disruption resulting from geopolitical and 164 market factors (e.g., production concentration and political instability of producing countries) as well 165 as the vulnerability of a user to supply disruptions. These methods have conceptualized, but not yet 166 operationalized, the "endpoints" of supply risk as impaired product functions and additional costs of production. The "Dilution of total stocks" approach, as suggested by (van Oers et al. 2002b; van Oers 167 and Guinée 2016), is also still in its conceptual stage of development (in purple). The approach 168 169 assumes that only dissipation into the ecosphere constitutes an absolute loss, not taking dissipation 170 within the technosphere into account. Therefore, the arrow in Figure 1 starts at the dissipation flow 171 into the ecosphere (as other methods start from primary mineral resource extraction). Furthermore, the 172 approach considers the total stock, i.e. the natural and the anthropogenic stock.

173 Based on the main impact mechanisms illustrated in Figure 1, methods were categorized into four 174 categories: Depletion, Future Efforts, Thermodynamic Accounting, and Supply Risk methods (Figure 175 2). This categorization is in line with those in previous literature (see e.g. Stewart and Weidema 2005; Steen 2006; Rørbech et al. 2014; Swart et al. 2015) adding the "Supply Risk" category. Since the 176 "dilution of total stocks" approach is not yet operational, it is not considered in this categorization but 177 178 further discussed in Berger et al. (2019). The grouping within a category is explained in the 179 corresponding category subsections (4.1-4.4). A special case is the Thermodynamic Rarity approach, 180 which can be assigned to two categories. On the one hand, it includes typical elements of 181 thermodynamic accounting, i.e. it accounts for exergy extraction assessed as the exergy difference 182 between a mineral resource as found in nature (e.g. copper in the ore) and a defined reference state 183 (see section 4.3). On the other hand, by assessing the cumulative exergy that would be needed to re-184 concentrate a mineral from crustal concentration to mine concentration, it also considers hypothetical 185 future efforts. The methods are discussed by category in the following section.

Depletion m	ethods					Supply Risk methods		
ADP (ultimate reserves)	ADP (ultimate Eco-scarcity A (2013)		EDIP 97				ESP GeoPolR	isk
ADP (reserve		AADP (update)	EDIP 2003				ESSENZ	
base)			LIME2 (midpoint)					
ADP (economic reserves)	ADP (economic reserves)					Thermodynamic		
							Accounting methods	·
Future Effor	Future Efforts methods							
Ore Grade Decrease	ORI (Ore Requirement	Eco-indicator 99	ReciPe 2008	SCP (Surplus Cost Potential)	LIME2 (endpoint)	EPS 2000/2015	CEENE	
	Indicator)	IMPACT 2002+				<u></u>		
	SOP (Surplus Ore Potential)	Stepwise 2006			Future Welfare Loss	Thermodynamic Rarity	Thermodynamic Rarity	

187

188 Figure 2: Overview of methods categorization according to underlying impact mechanisms; the Thermodynamic Rarity189 approach has elements of two categories.

190 4 Description of methods

191 The discussion of methods is organized into four sub-sections following the four method categories: 192 Depletion, Future Efforts, Thermodynamic Accounting, and Supply Risk methods. In each section, 193 methods are shortly presented and some method-category-specific assumptions and challenges are 194 discussed.

195 4.1 Depletion methods

196 The depletion concept is related to the reduction of a certain stock (or a set of stocks). This concept is 197 often used as a proxy for the availability of mineral resources: it is assumed that the extraction of 198 mineral resources from the ecosphere, i.e. the reduction of the natural stock, renders the mineral 199 resources less available. The characterization models of the ADP (Abiotic Depletion Potential) method 200 family are based on the ratio between the annual extraction of mineral resources and the square of a 201 natural stock estimate (Guinée and Heijungs 1995). Members of the ADP method family include the 202 Swiss Ecological Scarcity Method (Eco-scarcity) (Frischknecht and Büsser Knöpfel 2013), based on 203 ADP_{economic reserves}, and the AADP method (Schneider et al. 2011, 2015).

The variations of the ADP methods can be classified according to the stock estimate used in the 204 model, i.e., ADPultimate reserves. ADPreserve base, and ADPeconomic reserves (the former is based on crustal content 205 206 estimates, the latter two on United States Geological Survey (USGS) estimates (USGS 2010)). The 207 choice of stock estimate has implications on what is actually assessed by the model and has been extensively debated (see e.g. Guinée and Heijungs 1995; Hauschild and Wenzel 1998; van Oers et al. 208 209 2002a; Drielsma et al. 2016a; Sonderegger et al. 2017; and the discussion section). The Eco-scarcity 210 method theoretically embeds the ADP_{economic reserves} model in the method's distance-to-target approach, 211 i.e. comparing current extraction rates to (politically defined) target rates, but does not modify the

model as such. The AADP method considers that mineral resources may still be available after extraction from natural stocks as they are stored in anthropogenic stocks (e.g., electronic devices/waste). The characterization model therefore uses the sum of the natural stock (USGS resources (see <u>SMTable S1</u>) in the original version and ultimate reserves in the updated version) and the anthropogenic stock in the denominator. However, the mineral resource extraction rate in the numerator considers only extraction from natural stocks and not from anthropogenic stocks.

Other Depletion methods include EDIP 1997 and 2003 (Wenzel et al. 1997; Hauschild and Potting 2005) and LIME2_{midpoint} (Itsubo and Inaba 2012). The EDIP and LIME2_{midpoint} methods do not use the annual extraction to stock ratio but only the inverse of natural stock estimates (economic reserves in both cases). They might therefore not be depletion methods in a strict sense, though they are closely related. The argument for this approach is that the integration of current annual production into the indicator may underestimate future risks of mineral supply shortages for minerals that are not yet used in large volumes.

225 4.2 Future Efforts methods

Future Efforts methods may be generalized as seeking to assess the consequences of current mineral 226 227 resource use on societal efforts to extract a unit of mineral resource in the future. Ultimately, use of a 228 specific unit of mineral resource is implying a change in availability to future users of that very unit of 229 mineral resource. This requires future users either to re-use the same unit of the mineral resource (now 230 at a different quality), to use another unit of mineral resource, or to use another technology (Figure 231 S3). It is important to note that use of the future mineral resource or technology can be less impacting 232 and less expensive than the original use, in which case there is no negative impact on future users from 233 current dissipation (Stewart and Weidema 2005).

Most existing Future Efforts methods are based on the assumption that ore grades mined in the future will be lower (see Supplementary Material 1, section 3.1) and apply various proxy indicators to assess the related assumed increases in costs, e.g., surplus ore to be dealt with, surplus energy use, or surplus costs (see Table S2 for a list of all methods and their underlying modeling). The methods can be grouped into different subcategories according to what they include in their impact pathway.

Ore grade only methods – These methods focus on ore grades only without modeling any future efforts (they could therefore also be classified as depletion methods, using ore grades as the indicator). For this review, they are considered to be a proxy for potential future costs. Methods in this subcategory include the Ore Requirement Indicator (ORI) method (Swart and Dewulf 2013), the Ore Grade Decrease method (Vieira et al. 2012), and the Surplus Ore Potential (SOP) method (Vieira et al. 2016a; Vieira 2018). 245 **Ore grade – surplus energy methods** – These methods are based on the approach by (Müller-Wenk 246 1998), which uses grade-tonnage relationships based on assumed frequency distribution of concentrations in the earth's crust (see p. 78 in Goedkoop and Spriensma (2001) for a discussion of 247 248 assumptions and missing data sources). Surplus energy is calculated for an arbitrary future ore grade 249 (based on five times the cumulative production from 1990 and the grade-tonnage relationship) assuming no efficiency increases. Methods in this subcategory include the Eco-indicator 99 method 250 (Goedkoop and Spriensma 2001), the IMPACT 2002+ method (Jolliet et al. 2003), and the Stepwise 251 252 2006 method (Weidema et al. 2007).

Ore grade – surplus cost method – The assessment as implemented in ReCiPe 2008 (Goedkoop et al. 2013), evaluates grades and yields of all mines exploiting a particular deposit type in order to estimate marginal ore grade decline and assumes a constant cost in order to calculate surplus cost.

Cost only method – The Surplus Cost Potential (SCP) method (Vieira et al. 2016b; Vieira 2018) uses a similar line of thinking to the SOP method but it uses cost-tonnage instead of grade-tonnage relationships. Thus, this method is not related to ore grade decrease. Instead, it is based on the average gradient of cumulative cost-tonnage curves that are fitted to resource size and cost data from existing mines, and extrapolated to known mineral reserves or resources.

Average crustal concentration methods – These methods, implemented in EPS 2000/2015 (Steen 1999, 2016) and Thermodynamic Rarity (Valero and Valero, 2015), assume the mining of the average crustal concentration (of elements or minerals, respectively) and assess the corresponding energy or exergy costs.

Economics-only methods – These methods can be distinguished from the other Future Efforts 265 methods by not relating their modeling to future ore grades or future costs of mining activities. 266 267 Instead, they are based on mineral resource prices and economics, directly modeling economic relationships. Although the Future Welfare Loss (Huppertz et al. 2019) and the LIME2_{endpoint} approach 268 269 (Itsubo and Inaba 2012) both start from prices, they have differences. Since the economics only 270 methods are much less discussed in literature than other methods and internal discussions about their 271 differences were more intense than for other methods In order to make these differences clear, the two 272 methods are described in more detail below.

The Future Welfare Loss approach (De Caevel et al. 2012; Huppertz et al. 2019) takes its starting point in the recognition that a part of the future scarcity value of a resource is already included in the current price of the resource, more specifically as the economic rent. The rent is the net present value (NPV) of the expected future revenue from extracting the resource, and can be estimated as the difference between the price and the extraction cost of the resource. Although a part of the future scarcity value of a resource is thus already included in the resource price, it is not the full future value, since the current rent is calculated with the market discount rate, which is higher than the social discount rate. The current rent is therefore lower than what it would be using the social discount rate. This lower rent also leads to a faster depletion of the resource than what is socially optimal, i.e. when applying the social discount rate. The Future Welfare Loss is the difference between the rent calculated with the social discount rate and the rent calculated with the market discount rate. By using this as the indicator, the Future Welfare Loss approach assesses the potential externality of missed rents due to current overconsumption.

The LIME2_{endpoint} method is based on El Serafy's user cost (Itsubo and Inaba 2014). The basic idea behind the user cost concept is to generate a permanent income from earnings from the sale of finite resources (El Serafy 1989). In order to achieve this, a part of the earnings must be set aside as a capital investment to generate this permanent income. This part, also called the user cost, is the difference between earnings without capital investment and the permanent income. By using this as the indicator, the LIME2_{endpoint} method assesses the potential externality of missed future income due to a hypothetical lacking investment of earnings from the sale of finite resources.

293 4.3 Thermodynamic Accounting methods

294 Thermodynamic Accounting methods quantify the cumulative exergy (or energy) used in a product 295 system. The exergy of a system or resource is the maximum amount of useful work that can be 296 obtained from this system or resource when it is brought to (thermodynamic) equilibrium with its 297 environment, implying that an environment or reference state must be defined (Dewulf et al. 2008). 298 For metals and minerals, exergy methods account for either (i) the difference in exergy of these 299 resources compared to the reference state (CEENE and CExD methods), (ii) the exergy replacement 300 cost, defined as the exergy that would be needed to extract a mineral from a theoretical state of the 301 earth's crust, in which all mineral resources are completely dispersed (Thermodynamic Rarity 302 method), or (iii) the solar energy demand for the natural processes that has led to the current ore grades 303 of the extracted primary mineral resources (SED method).

304 The Cumulative Exergy Extraction from the Natural Environment (CEENE) method (Dewulf et al. 305 2007; Alvarenga et al. 2013; Taelman et al. 2014) and the Cumulative Exergy Demand (CExD) method (Bösch et al. 2007) both consider the approach proposed by Szargut et al. (1988), in which the 306 307 natural environment is the reference state. Thus, they account for the cumulative extraction of exergy 308 embedded in target mineral resources (e.g. copper) as the exergy difference between the mineral 309 resource as found in nature (e.g., copper in the ore) and a defined reference state in the natural environment (as defined by Szargut et al. (1988)). In Szargut's approach, the reference state is 310 311 represented by a reference compound that is considered to be the most probable product of the 312 interaction of the element with other common compounds in the natural environment and that typically 313 shows high chemical stability (e.g. SiO2 for Si) (De Meester et al. 2006). Although both methods are 314 based on the same approach, they have differences in operationalization (see discussion section).

315 The Thermodynamic Rarity method (Valero and Valero 2015) incorporates two aspects: exergy costs 316 (EC) and exergy replacement costs (ERC). The first evaluates the exergy cost required to mine and 317 beneficiate a given commodity with prevailing technologies, assuming current average concentrations 318 of mineral deposits and is similar to inventory accounting. The second aspect relates to the fact that 319 having minerals concentrated in ore bodies (and not dispersed throughout the crust) represents a "free bonus" provided by nature, which reduces the otherwise required energy costs of mining. The 320 321 reduction of this bonus when mines are depleted is quantified as so-called Exergy Replacement Costs 322 (ERC). These are defined as the cumulative exergy that would be needed to re-concentrate a mineral 323 from a completely dispersed state (denoted Thanatia) to the conditions of concentration and composition found in the original mines using prevailing technology. Hence, ERC can be seen as the 324 325 ultimate future effort that society would need to put into play when all mineral deposits become 326 depleted. In contrast to the Szargut approach, the Thermodynamic Rarity method does not include a 327 reference state in the form of reference compounds, but rather uses the composition and the average 328 concentration of the 294 most abundant minerals found in the earth's crust from which the 329 concentration exergy is calculated (Valero et al. 2018).

The Solar Energy Demand (SED) method (Rugani et al. 2011) is based on the emergy concept, whereby emergy is the amount of energy that was required across direct and indirect transformations to make a product or service (Odum 1996). The SED method estimates this total direct and indirect environmental work for minerals and metals, measured in equivalent solar energy units. For metals, this includes consideration of the global sedimentary cycle as well as mine concentrations, whereas minerals are assumed to be co-products of the global sedimentary cycle (Rugani et al. 2011, SI).

To summarize, CEENE and CExD consider the same impact mechanism, i.e. the exergy extraction assessed as the difference between a mineral resource as found in nature and a defined reference state in the natural environment. The ERC approach also considers an exergy difference, calculated as the exergy requirement to re-concentrate a mineral resource from a completely dispersed state to mine concentration. The SED method has yet another starting point and differentiates between minerals and metals.

342 4.4 Supply Risk methods

Three Supply Risk methods based on the criticality concept have been developed in the context of LCA: The Geopolitical Supply Risk (GeoPolRisk) method (Gemechu et al. 2016; Helbig et al. 2016a;

- 345 Cimprich et al. 2017b), the Economic Scarcity Potential (ESP) method (Schneider et al. 2014), and the
- 346 Integrated Method to Assess Resource Efficiency (ESSENZ) (Bach et al. 2016), which is an extension

347 and update of the ESP method. The criticality concept typically includes considerations of potential 348 supply disruption (e.g. due to trade barriers, armed conflicts, economic and technological limitations of exploration and extraction, environmental regulations, and natural disasters) and vulnerability to 349 supply disruption (e.g. assessed by potential (socio-economic) impacts of this supply disruption), and 350 351 it typically considers 10-year time horizons (defined within the task force as a short time horizon) (see e.g. Achzet and Helbig 2013; Graedel and Reck 2015). In accordance with classical risk theory, we 352 353 refer to the three methods mentioned above as "Supply Risk methods", whereby supply risk is 354 conceptualized as a function of supply disruption probability and vulnerability (Cimprich et al. 2019). 355 Importantly, our conceptualization of "supply risk" deviates from the common use of this term in the 356 criticality literature, which, as argued by Glöser et al. (2015) and Frenzel et al. (2017), refers to supply 357 disruption probability only.

While supply risk assessment concerns potential "outside-in" impacts of supply disruptions on a given 358 359 product system (for example, impaired product performance, increased production costs, and/or lost 360 revenue due to production shutdowns), the characterization models of LCA traditionally concern 361 "inside-out" impacts of a product system on the environment (for example, climate change, 362 acidification, and particulate matter formation) (Cimprich et al. 2019). Another key difference from "traditional" LCA characterization models is that, as the total supply risk associated with a product 363 system is a function of its entire supply chain, supply risk is evaluated for both elementary flows and 364 intermediate flows; which here are collectively termed "inventory flows" following (Cimprich et al. 365 366 2019).

367 The ESP method, along with the ESSENZ method that supersedes it, directly build upon criticality 368 concepts and thereby include many factors relevant to supply disruption probability – for ESSENZ 369 these include mining capacity, primary material use, concentration of reserves and production, 370 company concentration, price volatility, demand growth, feasibility of exploration projects, trade barriers, political stability and co-production. The GeoPolRisk method, on the other hand, focuses 371 372 more narrowly on geopolitical stability. Although the ESSENZ method includes other supply disruption probability factors besides political stability, the impact pathways for the other factors are 373 374 conceptually similar to those for political stability. We therefore focus on this indicator for the purpose 375 of describing and comparing the GeoPolRisk and ESSENZ methods. Supply disruption probability 376 depends on the geopolitical stability of countries from which inventory flows are sourced. To measure 377 political stability all three methods apply a different set of the Worldwide Governance Indicators (WGIs) published by the World Bank (2018). Supply disruption probability is also a function of 378 379 mediating factors that influence the likelihood and severity of supply disruptions arising from political 380 instability. All three methods use the production concentration, typically measured by the Herfindahl-381 Hirschman Index (HHI), as a mediating factor. All else being equal, higher production concentration 382 reduces the potential for supply-chain restructuring to mitigate supply disruptions, and therefore 383 increases supply risk. While the GeoPolRisk method weights the WGI values of upstream raw 384 material producing countries by their import shares to downstream product manufacturing countries, 385 the ESP and ESSENZ methods calculate a global average WGI index using country production shares of raw materials. Supply disruption *vulnerability* reflects the impacts of supply disruptions that may 386 occur (Helbig et al. 2016b). Whereas the ESP and ESSENZ methods consider larger amounts of 387 388 materials used in the considered product system to indicate higher vulnerability, the GeoPolRisk 389 method considers all materials to be of equal importance regardless of the amounts in which they are 390 used. An extension of the GeoPolRisk method by (Cimprich et al. 2017a) also considers 391 substitutability of materials as a mediating factor for vulnerability. A more detailed review of the 392 GeoPolRisk, ESP, and ESSENZ methods can be found in (Cimprich et al. 2019).

393 5 Criteria-based assessment of methods

All 27 methods were assessed <u>by method developers and/or one to three other reviewers from the task</u> force_using a set of 45 mainly descriptive criteria grouped into seven main categories_(see <u>Supplementary Material 2</u>). While the Life Cycle Initiative provided the seven main categories, the mineral resources-specific sub-criteria were developed by the task force through an iterative process to arrive at a comprehensive assessment scheme-(SM2). Here, we focus on those criteria that highlighted differences between methods and therefore can be used to guide application-dependent use of the methods, while highlighting areas for further methodological development (see Berger et al. (2019)).

401 **General characteristics** – Since the methods differ in the impacts intended to be assessed, their 402 characterization factors have different units, even within method categories. Furthermore, the methods 403 consider different time horizons (from a few years to hundreds of years). As discussed in previous 404 sections, all "traditional" LCA methods have an inside-out perspective whereas Supply Risk methods 405 have been developed with an outside-in perspective.

406 **Completeness of scope** – All methods have a global scope and no further geographical resolution, except for the GeoPolRisk, which is at the country level. With regard to the categorization into 407 408 midpoint and endpoint methods, our result is consistent with existing literature (e.g. EC-JRC (2011)). 409 Depletion and Thermodynamic Accounting methods are considered to be midpoint methods. Within Future Efforts methods, "Ore grade only"-methods (see section 4.2) are considered midpoint methods, 410 411 whereas the others are considered endpoint methods. The exception is the SOP method, which is 412 considered to be a midpoint in ReCiPe 2016 and to be an endpoint in LC-Impact. This illustrates that 413 within the midpoint and endpoint indicators, there is no general agreement yet on what *the* midpoint or the endpoint should be and the distinction between the two is not always obvious. Supply Risk 414 415 methods are considered midpoint methods.

416 Coverage of impact mechanisms and resources(Environmental) relevance – Our classification of 417 methods reflects to some extent the (environmental) impact mechanisms considered in order to assess impacts, i.e. Depletion methods consider depletion rates, Thermodynamic Accounting consider exergy 418 extraction from nature, and Supply Risk methods assess supply disruption probability and 419 420 vulnerability. With Future Efforts methods this is less clear: By assessing (future) additional efforts needed to access mineral resources, they are implicitly also assessing aspects of depletion. Not all 421 impact mechanisms considered are environmental. Those for the GeoPolRisk method for example are 422 423 primarily socioeconomic and often there is a mixture of environmental and economic mechanisms as 424 for example in the ADP methods. Existing methods have been designed for mineral resources and, 425 except for the Thermodynamic Accounting methods, typically have limited, if any, coverage of other 426 natural resources (e.g. water, land, biotic resources).

427 Peer review, data sources, and uncertaintyScientific robustness and certainty – Except for 428 ReCiPe 2008, all methods were peer reviewed. Characterization factors based on stock estimates 429 throughout the different methods often rely on data from the USGS, with original publication dates of 430 the data differing widely from the 1990's to almost up to date. Eco-indicator 99 (and hence IMPACT 431 2002+ and Stepwise 2006, which are based on it) are based on non-transparent data sources (see 432 Goedkoop and Spriensma 2001, p.78, for a discussion of assumptions and data sources).

433 Documentation, transparency, and reproducibility – All methods are documented – although with
434 varying levels of detail – and the underlying models and the input data needed are accessible in most
435 cases. However, some of the documentation, models, and data are not accessible for free.

436 Applicability and ease of implementation – All Depletion and Future Efforts methods are compatible with existing Life Cycle Inventories (LCIs), which provide elementary flows in kg primary 437 438 resource. Thermodynamic Accounting methods are also compatible except for Thermodynamic Rarity. 439 The Supply Risk methods are based on both elementary and intermediate flows and are therefore not 440 yet fully compatible with "traditional" LCIs. The coverage of elementary flows varies widely from 9 441 to over 70 elementary flows, being 40 on average (for details see Supplementary Material 2). The lack 442 of characterization factors for rare earth metals has been highlighted for many methods; and mineral 443 aggregates are rarely covered (only Eco-scarcity, SOP/SCP, and Supply Risk methods).

444 6 Discussion of methods

Some of the main points of contention, particularly in relation to Depletion and Future Efforts methods, pertain to a broader discussion around resource depletion and scarcity - and whether these are real or perceived issues. Significant research efforts have been undertaken within the broader geoscience, sustainable development, mineral economics and industrial ecology research communities to understand the complexities underpinning their assessment. These studies highlight the fluidity of

- 450 mineral reserve and resource estimates (Meinert et al. 2016), the complexity and shortcomings of 451 metrics such as ore grades for assessing resource depletion (West 2011; Priester et al. 2019), the 452 general uncertainty over society's future mineral resource needs and the degree to which mineral 453 exploration will be successful in meeting these (Ali et al. 2017), and the ultimate impact of this on 454 commodity prices and policy requirements (Tilton et al. 2018).
- The following subsections discuss each of our four method categories (Depletion, Future Efforts,Thermodynamic Accounting, and Supply Risk) in more detail.

457 6.1 Depletion methods

- The main points for discussion of depletion methods are the choice of stock estimate, the use of extraction to stock ratios or stocks only, and the inclusion of anthropogenic stocks.
- 460 While the "ultimately extractable reserves" is the relevant stock estimate in terms of depletion of the 461 natural stock, it will never be exactly known because of its dependence on future technological 462 developments (Guinée and Heijungs 1995) and unavoidable geologic uncertainty. Therefore, it can only be approximated and ADPultimate reserves is currently considered the best proxy according to the ADP 463 464 developers (Guinée and Heijungs 1995; van Oers et al. 2002b; van Oers and Guinée 2016). This 465 recommendation is mainly based on the fact that estimates of economic reserves and the reserve base fluctuate over time as they are defined by economic considerations not directly related to the depletion 466 problem, thus resulting in unstable and continuously changing estimates. However, the use of ultimate 467 reserves has been criticized by geologists as inappropriate for the assessment of mineral resource 468 469 availability because a majority of the material contained in the earth's crust may always remain unavailable for extraction (Drielsma et al. 2016a). The use of ADP_{reserve base} and ADP_{economic reserves} has 470 471 also been criticized as irrelevant to assess the relative rate of long-term depletion of the natural stock, 472 since both are a function of the level of exploration undertaken, which is based on economic considerations (Drielsma et al. 2016b). They should be interpreted as a snapshot taken at a certain 473 474 point in time that reflects a subset of the reserves currently available, so they imply a short to mid-term 475 time horizon (up to a few decades). Therefore, they could rather be seen as an indicator for potential 476 mineral resource availability issues related to mid-term (a few decades) physical-economic resource scarcity (see also Berger et al. 2019). Furthermore, as they vary in time, the characterization factors 477 478 would need to be updated on a regular basis. Since the USGS no longer estimates the reserve base 479 (USGS 2010), this is only possible for ADPeconomic reserves (stock estimate and extraction rates) and 480 ADP_{ultimate reserves} (extraction rates).

481 The inclusion of current annual extraction in the characterization model has advantages and 482 disadvantages. On the one hand, the inclusion of extraction may lead to an underestimation of future 483 risks of supply shortages for minerals that are not used in large volumes, as suggested by the 484 developers of the LIME method. On the other hand, even the authors of the LIME2_{midpoint} method discuss extraction rates as a relevant factor, since they provide an indication for the risk of depletion. 485 486 The definition of what constitutes the flow that renders mineral resources unavailable is often not 487 explicitly stated in available methods. The extraction of mineral resources from nature to technosphere 488 is usually approximated with production data, which refer to the net production of target metals rather 489 than the overall quantities extracted from nature to technosphere (i.e. flows of material which end up 490 in tailings, waste rock, or as emissions to nature are not accounted for). This is equal to the implicit 491 assumption that the efficiency of concentrate production is similar for all metals and does not 492 influence the relative results of the ADP indicator. This assumption may not hold in all cases, 493 particularly for co- and by-product commodities.

494 Recent conceptual developments of the ADP and the AADP method also consider anthropogenic 495 stocks. Accordingly, the extraction from nature to technosphere is not considered to automatically 496 render mineral resources inaccessible. It is rather the type of transformation and the destination of the 497 mineral resource that determine whether it remains (potentially) useable. The depletion of the total stock (natural + anthropogenic) only happens if the mineral resource is emitted or diluted (terms used 498 499 in van Oers et al. (2002)) or dissipated (term used in Stewart and Weidema (2005)) and remains 500 unrecoverable. While the AADP characterization model includes the sum of the natural and the 501 anthropogenic stocks in the denominator, the numerator only accounts for mineral resource extraction 502 from natural stocks.

To summarize, the ADP_{ultimate reserves} may be considered the most suitable<u>existing</u> approach to assess the relative rate of long-term depletion of natural mineral stocks. As suggested by the method developers, ADP methods based on other stock estimates could be used for sensitivity analysis (van Oers et al. 2002b) or they might be used with a different interpretation, as discussed above. In addition, other depletion methods, i.e. EDIP/ LIME2_{midpoint} or AADP, could be used for sensitivity analysis. As described above, none of the existing methods fully reflects the issue of dissipation (for a more detailed discussion of the dissipation concept see Berger et al. (2019)).

510 6.2 Future Efforts methods

511 The main points for discussion of Future Efforts methods are the assumption of declining ore grades 512 and the data upon which the different methods are based. The Economics-only methods, LIME2_{endpoint} 513 and Future Welfare Loss, are discussed separately.

514 The main assumption of many Future Efforts methods is that preferential extraction of known higher-

515 grade mineral resources will lead to long-term decline in the average mineral resource grade. This is

516 an assumption for the long-run future and therefore impossible to prove or falsify. At first glance, it

517 appears to be supported by an observed long-term (over the past century) trend of declining mined ore

518 grades for a variety of (but not all) mineral commodities and regions (Crowson 2012; Mudd et al. 519 2013, 2017). However, there is confounding influence of technology, economic, and market conditions: when technology improves or when growth in demand exceeds growth in supply, a decline 520 in mined ore grades would be expected, independent of mineral resource depletion considerations 521 522 (West 2011; Northey et al. 2017). When supply capacity exceeds demand, mined ore grades have been observed to increase despite continued extraction (e.g., gold between 2014-2017). Furthermore, when 523 demand triggers investments in exploration, deposits are typically found and code based (i.e. JORC, 524 525 CRIRSCO, NI43-101, etc.) mineral resources or reserves defined with grades profitable under the 526 foreseeable economic situation. Currently, there are no studies that assess in detail how much these 527 competing factors have contributed to historical ore grade changes. Therefore, the methods making use 528 of the declining ore grade concept are effectively using correlations rather than seeking to identify 529 causal factors of grade decline. Furthermore, the Ore Requirement Indicator (ORI) and the Surplus 530 Cost Potential (SCP) methods base their indicators on observed ore grade decline or cost increase 531 during a period with substantial growth in mineral demand as well as in costs and prices. The validity 532 of their assumption of a causal relationship between consumption and ore grade decline or cost 533 increase can therefore be questioned and the underlying data used should ideally be tested over multiple commodity price cycles. The ReCiPe2008 approach (based only on existing mines) and 534 535 methods using grade-tonnage relationships based on data from existing mines and known deposits 536 (Ore Grade Decrease and Surplus Ore Potential) may be criticized for extrapolating data of known deposits to all potentially accessible deposits, including unknown deposits. As mentioned in section 5, 537 538 Eco-indicator 99 (and hence IMPACT 2002+ and Stepwise 2006, which are based on it) is based on 539 non-transparent data sources (see Goedkoop and Spriensma 2001, p. 78). Furthermore, these methods 540 assess the surplus energy consequences of extracting natural resources from lower grade deposits at an 541 arbitrarily chosen time horizon, i.e. when extraction reaches 5 times cumulated extraction before 1990. 542 Similarly, EPS 2000/2015 and Thermodynamic Rarity consider extraction from a completely 543 dispersed state of all elements and minerals, respectively. None of these methods model an ore grade 544 decline (and its consequences) based on extraction data but only consider an assumed change in ore grades at a future point in time. 545

546 Among the ore grade methods, SOP has the most solid data foundation. The cumulative grade-tonnage 547 distributions underpinning the method provide a physical basis for comparing the likely relative (but 548 not absolute) impacts of mineral extraction, based upon current technical and economic supply 549 capabilities. The main weakness of SOP is that it is assuming mining from highest to lowest grade and 550 not explicitly accounting for competing factors such as technology and economic considerations. 551 Besides the discussion on decreasing ore grades, data on future mineral resources and technologies will of course always be inherently uncertain, and the different practical implementations of the future 552 553 efforts methods will therefore always depend on different forecasts and assumptions.

554 Economics-only methods, i.e. Future Welfare Loss and LIME2_{endpoint}, do not rely on a prediction of 555 future ore grades or efforts and hence avoid the corresponding difficulties and uncertainties. Instead, they model (potential) economic externalities and thereby introduce relative (not absolute) 556 557 uncertainties of discounting methods, i.e. uncertainties that affect all resources equally and therefore 558 not their relative ranking. The Future Welfare Loss and the LIME2_{endpoint} methods can be seen as complementary, since they address two different economic externalities, namely that caused by the 559 560 difference between the private and social discount rates (Future Welfare Loss) and that caused by 561 insufficient reinvestment of the economic rent (LIME2_{endpoint}).

562 6.3 Thermodynamic Accounting methods

Thermodynamic Accounting methods do not explicitly link used amounts of mineral resources to changes in their availability. Furthermore, the Thermodynamic Rarity method does not yet provide CFs fitting to elementary flows in Life Cycle Inventory databases. However, Thermodynamic Accounting methods may be used in LCA as proxy for (overall) environmental impacts (like Cumulative Energy Demand; Huijbregts et al. 2006, 2010; Steinmann et al. 2017) or for efficiency and renewability assessment as in Dewulf et al. (2005).

569 The CEENE method was developed with the aim of addressing some of the shortcomings of the CExD 570 method, particularly with regard to land use and renewable energies (for a detailed discussion of the differences between the methods see Dewulf et al. (2007)). With regard to mineral resources, CExD 571 calculates the exergy of metals from the whole metal ore that enters the technosphere, whereas 572 573 CEENE only regards the metal-containing minerals of the ore, with the argument that the tailings from 574 the beneficiation are often not chemically altered when deposited (Dewulf et al. 2007). Furthermore, 575 the CEENE method has been further improved and extended for land use (Alvarenga et al. 2013) and 576 occupation of the marine environment (Taelman et al. 2014).

577 The Thermodynamic Rarity approach (particularly through the ERC concept) can be seen as assessing the geological and technological availability of mineral resources, assessed as the cumulative exergy 578 579 that would be needed to re-concentrate a mineral from a completely dispersed state to the conditions of concentration and composition found in the original mines using prevailing technology. Therefore, it 580 581 is related to the Future Efforts methods (see according sections) and – although it was not purposely 582 developed to be incorporated into the LCA structure – is the closest in addressing the availability of 583 mineral resources for human purposes of the Thermodynamic Accounting approaches. On the other 584 hand, the ERC approach is also different, e.g. with regard to the reference state, which might be 585 considered less mature than the one of Szargut. Furthermore, the underlying hypotheses and 586 assumptions lack on clear cause-and-effect relationships (e.g. Thanatia as the final outcome of 587 humankind, in the very long timeframe, and the need for re-concentration of dispersed metals with

current technology). And finally, its role (thermodynamic accounting or future efforts or both?) and itsintegration into LCA still need to be clarified.

In case there is interest to consider the value of resources for beneficiaries other than humans as well, e.g. biota, or to consider the indirect value for humans (provided through the value for others, like natural ecosystem and their biotic elements), the SED might serve this purpose. Like emergy synthesis, SED looks at a system as embedded in the larger natural system that underpins it, and includes all direct and indirect inputs to support it, independently of the actual usefulness of the ecological and technological inputs delivered to the systems under study (Raugei et al. 2014).

596 6.4 Supply Risk methods

597 In comparison to the GeoPolRisk method, the ESP and ESSENZ methods serve different goals and 598 scopes: whereas the latter two aim to provide characterization factors with global applicability – much 599 like "traditional" LCIA mineral resource impact assessment methods - the GeoPolRisk method aims 600 to highlight differences in supply risk between countries based on trading relationships. Accordingly, 601 the ESP method and the more comprehensive-ESSENZ method may be used for calculating global 602 average supply risk characterization factors that can be applied by multinational companies having 603 locations all over the world. The GeoPolRisk method, on the other hand, may be used for country-604 level supply risk assessment. Since the short-term and outside-in-perspectives of Supply Risk methods are different from those of "traditional" LCIA methods there have been intense discussions without 605 consensus in the task force about whether they should be seen as (i) being clearly outside of LCA, (ii) 606 607 being complementary (e.g. as part of a broader life cycle sustainability assessment (LCSA) framework 608 (Schneider et al. 2014; Sonnemann et al. 2015)), or (iii) even being another part of LCA (see also 609 Berger et al. (2019)). A more detailed discussion of the three methods can be found in (Cimprich et al. 610 2019).

611 7 Conclusions

612 27 LCIA methods assessing impacts of mineral resource use were thoroughly reviewed. The methods 613 were categorized based on modeled impact mechanisms, and assessed using an extensive set of 614 criteria. The concepts underlying the method categories and the individual methods were described, 615 compared, and discussed. Of the four main method categories (Figure 2), we consider Depletion and 616 Future Efforts methods more "traditional" LCIA methods, whereas Thermodynamic Accounting and 617 Supply Risk methods are rather providing complementary information that might be useful for more 618 encompassing life cycle approaches.

619 Of the Depletion methods, ADP_{ultimate reserves} provides the most constant assessment of the relative 620 potential of long-term depletion of natural stocks of mineral resources since crustal content estimates have been quite stable over time. Other variations of the ADP method might be used for sensitivity analysis or with a different interpretation. For example, $ADP_{economic reserves}$ could be used to assess potential resource availability issues related to mid-term (a few decades) physico-economic resource scarcity. New conceptual developments – further discussed in Berger et al (2019) – strive towards a "dissipation" approach by including the anthropogenic stock and dissipation flows in the modeling.

Ore grade-related Future Efforts methods often assume that mining takes place from highest to lowest 626 627 grade although different ore grades are mined in parallel. Furthermore, they do not explicitly account for competing factors such as technology and economic considerations. Therefore, further studies 628 would be needed to confirm that the assumptions behind the ore grade-related Future Efforts methods 629 630 are nonetheless valid in the long run. Among these methods, SOP has the most solid data foundation. The ORI and the SCP methods rely on empirical data from a period with substantial growth in mineral 631 demand and prices, which is one reason why their assumption of a causal relationship can be 632 633 questioned. The underlying data should ideally be tested over multiple commodity price cycles to 634 validate the assumed relationships. Some approaches need more discussion because they consider 635 other aspects or have not been discussed extensively before. One of these approaches is the Exergy 636 Replacement Costs (ERC) as implemented in Thermodynamic Rarity, which provides a different 637 measurement for ore quality than the other ore grade approaches. Another group of methods is the Economics-only methods. They use market prices instead of using physical data on future ore grades, 638 technologies and supply-demand relationships. Thereby, they consider market agents to have 639 640 privileged access to information on aspects like future applications of the resource, future backstop 641 technologies, recycling potentials, the evolution of reserves and extraction costs, so that all these aspects will be taken into account in the market price (Huppertz et al. 2019). In this way, the 642 643 uncertainty of the economic information includes the markets' assessment of the uncertainty of the 644 physical information.

645 The Thermodynamic Accounting methods include three different approaches. CEENE and CExD 646 calculate the exergy difference between the mineral resource as found in nature (e.g., copper in the ore) and a reference compound in the natural environment. The CEENE method has been developed to 647 648 address some shortcomings of the CExD method. The ERC approach includes the aspect of 649 concentrations in mines and considers minerals instead of reference compounds. It is thereby similar 650 to CEENE and CExD (by assessing a difference in exergy) but it also contains elements of Future 651 Efforts methods (by considering mineral resource quality in mines). However, the approach still needs 652 to be integrated into the LCA structure as no characterization factors compatible with LCI databases 653 are available yet. Finally, the SED method estimates the total direct and indirect solar energy 654 requirement to concentrate the mineral resource to its current state.

- Supply Risk methods have an "outside-in" perspective compared to "traditional" LCIA methods with their "inside-out" perspective, thus complementing environmental LCA with a socio-economic risk perspective (see also Berger et al. (2019)). There was no agreement in the task force whether they are in the scope of LCA or only part of LCSA. In any case, some practitioners might be interested in the short-term and outside-in-perspectives of these methods.
- Based on the insights from this thorough review and assessment of existing methods, which served as
 an input to the Pellston Workshop®, recommendations for application-dependent use of existing
 methods, along with areas for further methodological development have been developed in a Pellston
 Workshop®, a report of which are-is presented in the second part of this paper series (Berger et al.
 2019).

665 Disclaimer

666 The views, interpretations and conclusions presented in this paper are those of the authors and do not 667 necessarily reflect those of their respective organizations.

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674 8 References

- Achzet B, Helbig C (2013) How to evaluate raw material supply risks—an overview. Resour Policy
 38:435–447. doi: 10.1016/j.resourpol.2013.06.003
- Ali SH, Giurco D, Arndt N, et al (2017) Mineral supply for sustainable development requires resource
 governance. Nature 543:367–372. doi: 10.1038/nature21359
- Alvarenga RAF, Dewulf J, Van Langenhove H, Huijbregts MAJ (2013) Exergy-based accounting for
 land as a natural resource in life cycle assessment. Int J Life Cycle Assess 18:939–947. doi:
 10.1007/s11367-013-0555-7
- Bach V, Berger M, Henßler M, et al (2016) Integrated method to assess resource efficiency –
 ESSENZ. J Clean Prod 137:118–130. doi: 10.1016/j.jclepro.2016.07.077
- Berger M, Sonderegger T, Alvarenga R, et al (2019) Mineral resources in Life Cycle Impact
 Assessment Part II: Recommendations on application-dependent use of existing methods and
 on future method development. Int J Life Cycle Assess
- Bösch ME, Hellweg S, Huijbregts MAJ, Frischknecht R (2007) Applying cumulative exergy demand
 (CExD) indicators to the ecoinvent database. Int J Life Cycle Assess 12:181–190. doi:
 10.1065/lca2006.11.282
- 690 Cimprich A, Bach V, Helbig C, et al (2019) Raw material criticality assessment as a complement to
 691 environmental life cycle assessment: Examining methods for product-level supply risk
 692 assessment. J Ind Ecol 1–11. doi: 10.1111/jiec.12865
- 693 Cimprich A, Karim KS, Young SB (2017a) Extending the geopolitical supply risk method: material
 694 "substitutability" indicators applied to electric vehicles and dental x-ray equipment. Int J Life
 695 Cycle Assess. doi: 10.1007/s11367-017-1418-4
- 696 Cimprich A, Young SB, Helbig C, et al (2017b) Extension of geopolitical supply risk methodology :
 697 Characterization model applied to conventional and electric vehicles. J Clean Prod 162:754–763.
 698 doi: 10.1016/j.jclepro.2017.06.063
- 699 Crowson P (2012) Some observations on copper yields and ore grades. Resour Policy 37:59–72. doi:
 700 10.1016/j.resourpol.2011.12.004
- De Caevel B, Standaert S, Van Overbeke E (2012) How to correct price for monetising non-renewable
 resource consumption? In: SETAC Europe 22nd Annual Meeting Extended Abstracts. Berlin
- De Meester B, Dewulf J, Janssens A, Van Langenhove H (2006) An improved calculation of the
 exergy of natural resources for Exergetic Life Cycle Assessment (ELCA). Environ Sci Technol
 40:6844–6851. doi: 10.1021/es060167d

- Dewulf J, Benini L, Mancini L, et al (2015) Rethinking the Area of Protection "Natural Resources" in
 Life Cycle Assessment. Environ Sci Technol 49:5310–5317. doi: 10.1021/acs.est.5b00734
- Dewulf J, Boesch ME, De Meester B, et al (2007) Cumulative Exergy Extraction from the naural
 environment (CEENE): a comprahensive Life Cycle Impact Assessment method for resource
 accounting. Environ Sci Technol 41:8477–8483. doi: 10.1021/es0711415
- Dewulf J, Van Langenhove H, Muys B, et al (2008) Exergy: Its potential and limitations in
 environmental science and technology. Environ Sci Technol 42:2221–2232. doi:
 10.1021/es071719a
- Dewulf J, Van Langenhove H, Van De Velde B (2005) Exergy-based efficiency and renewability
 assessment of biofuel production. Environ Sci Technol 39:3878–3882. doi: 10.1021/es048721b
- Drielsma JA, Allington R, Brady T, et al (2016a) Abiotic Raw-Materials in Life Cycle Impact
 Assessments: An Emerging Consensus across Disciplines. Resources 5:12. doi:
 10.3390/resources5010012
- Drielsma JA, Russell-Vaccari AJ, Drnek T, et al (2016b) Mineral resources in life cycle impact
 assessment—defining the path forward. Int J Life Cycle Assess 21:85–105. doi: 10.1007/s11367015-0991-7
- EC-JRC (2011) International Reference Life Cycle Data System (ILCD) Handbook:
 Recommendations for Life Cycle Impact Assessment in the European context. European
 Commission, Joint Research Centre, Institute for Environment and Sustainability, Ispra
- El Serafy S (1989) The Proper Calculation of Income from Depletable Natural Resources. In:
 Environmental Accounting for Sustainable Development. The International Bank for
 Reconstruction and Development, The World Bank, Washington, D.C.
- 728 Fraunhofer (2018) Science meets Business Workshop, March 6, 2018, Stuttgart, Germany
- Frenzel M, Kullik J, Reuter MA, Gutzmer J (2017) Raw material ' criticality '— sense or nonsense ? J
 Phys D Appl Phys 50:. doi: 10.1088/1361-6463/aa5b64
- Frischknecht R, Büsser Knöpfel S (2013) Swiss Eco-Factors 2013 according to the Ecological Scarcity
 Method. Federal Office for the Environment FOEN, Bern
- Gemechu ED, Helbig C, Sonnemann G, et al (2016) Import-based Indicator for the Geopolitical
 Supply Risk of Raw Materials in Life Cycle Sustainability Assessments. J Ind Ecol 20:154–165.
 doi: 10.1111/jiec.12279
- Glöser S, Tercero Espinoza L, Gandenberger C, Faulstich M (2015) Raw material criticality in the
 context of classical risk assessment. Resour Policy 44:35–46. doi:

- 738 10.1016/j.resourpol.2014.12.003
- Goedkoop M, Heijungs R, de Schryver A, et al (2013) ReCiPe 2008. A LCIA method which
 comprises harmonised category indicators at the midpoint and the endpoint level.
 Characterisation. Ministerie van VROM, Den Haag
- Goedkoop M, Spriensma R (2001) The Eco-indicator 99 A damage oriented method for Life Cycle
 Impact Assessment. Amersfoort, The Netherlands
- Graedel TE, Reck BK (2015) Six Years of Criticality Assessments What Have We Learned So Far? J
 Ind Ecol 20:692–699. doi: 10.1111/jiec.12305
- Guinée JB, Heijungs R (1995) A proposal for the definition of resource equivalency factors for use in
 product life-cycle assessment. Environ Toxicol Chem 14:917–925. doi: 10.1002/etc.5620140525
- Hauschild M, Potting J (2005) Spatial differentiation in Life Cycle impact assessment The EDIP2003
 methodology
- Hauschild M, Wenzel H (1998) Environmental Assessment of Products Volume 2: Scientific
 Background. Springer US
- Helbig C, Gemechu ED, Pillain B, et al (2016a) Extending the geopolitical supply risk indicator:
 Application of life cycle sustainability assessment to the petrochemical supply chain of
 polyacrylonitrile-based carbon fibers. J Clean Prod 137:1170–1178. doi:
 10.1016/j.jclepro.2016.07.214
- Helbig C, Wietschel L, Thorenz A, Tuma A (2016b) How to evaluate raw material vulnerability An
 overview. Resour Policy 48:13–24. doi: 10.1016/j.resourpol.2016.02.003
- Huijbregts MAJ, Hellweg S, Frischknecht R, et al (2010) Cumulative energy demand as predictor for
 the environmental burden of commodity production. Environ Sci Technol 44:2189–2196. doi:
 10.1021/es902870s
- Huijbregts MAJ, Rombouts LJA, Hellweg S, et al (2006) Is cumulative fossil energy demand a useful
 indicator for the environmental performance of products? Environ Sci Technol 40:641–648. doi:
 10.1021/es051689g
- Huppertz T, Weidema BP, Standaert S, et al (2019) The Social Cost of Sub-Soil Resource Use.
 Resources 8:. doi: 10.3390/resources8010019
- Itsubo N, Inaba A (2012) LIME 2 Life-cycle Impact assessment Method based on Endpoint
 modeling Summary. JLCA Newsl Life-Cycle Assess Soc Japan 16
- Itsubo N, Inaba A (2014) LIME2 Chapter 2: Characterization and Damage Evaluation Methods.
 JLCA Newsl Life-Cycle Assess Soc Japan 151

- Jolliet O, Margni M, Charles R, et al (2003) IMPACT 2002 +: A New Life Cycle Impact Assessment
 Methodology. Int J Life Cycle Assess 8:324–330. doi: 10.1007/BF02978505
- Meinert LD, Jr GRR, Nassar NT (2016) Mineral Resources: Reserves, Peak Production and the
 Future. doi: 10.3390/resources5010014
- Mudd GM, Jowitt SM, Werner TT (2017) The world's by-product and critical metal resources part I:
 Uncertainties, current reporting practices, implications and grounds for optimism. Ore Geol Rev
 86:924–938. doi: 10.1016/j.oregeorev.2016.05.001
- Mudd GM, Weng Z, Jowitt SM (2013) A detailed assessment of global Cu resource trends and
 endowments. Econ Geol 108:1163–1183. doi: 10.2113/econgeo.108.5.1163
- Müller-Wenk R (1998) Depletion of Abiotic Resources Weighted on the Base of "Virtual" Impacts of
 Lower Grade Deposits in Future. St. Gallen
- Northey SA, Mudd GM, Werner TT, et al (2017) The exposure of global base metal resources to water
 criticality, scarcity and climate change. Glob Environ Chang 44:109–124. doi:
 10.1016/j.gloenvcha.2017.04.004
- Nuss P, Eckelman MJ (2014) Life cycle assessment of metals: A scientific synthesis. PLoS One 9:1–
 12. doi: 10.1371/journal.pone.0101298
- Odum HT (1996) Environmental accounting: Emergy and environmental decision making. John Wiley
 & Sons, Inc.
- Priester M, Ericsson M, Dolega P, Löf O (2019) Mineral grades: an important indicator for
 environmental impact of mineral exploitation. Miner Econ 32:49–73. doi: 10.1007/s13563-01800168-x
- Raugei M, Rugani B, Benetto E, Ingwersen WW (2014) Integrating emergy into LCA: Potential added
 value and lingering obstacles. Ecol Modell 271:4–9. doi: 10.1016/j.ecolmodel.2012.11.025
- Rørbech JT, Vadenbo C, Hellweg S, Astrup TF (2014) Impact assessment of abiotic resources in
 LCA: Quantitative comparison of selected characterization models. Environ Sci Technol
 48:11072–11081
- Rugani B, Huijbregts MAJ, Mutel CL, et al (2011) Solar Energy Demand (SED) of Commodity Life
 Cycles. Environ Sci Technol 45:5426–5433. doi: 10.1021/es103537f
- Schneider L, Berger M, Finkbeiner M (2011) The anthropogenic stock extended abiotic depletion
 potential (AADP) as a new parameterisation to model the depletion of abiotic resources. Int J
 Life Cycle Assess 16:929–936. doi: 10.1007/s11367-011-0313-7
- 801 Schneider L, Berger M, Finkbeiner M (2015) Abiotic resource depletion in LCA background and

- update of the anthropogenic stock extended abiotic depletion potential (AADP) model. Int J Life
 Cycle Assess 20:709–721. doi: 10.1007/s11367-015-0864-0
- Schneider L, Berger M, Schüler-Hainsch E, et al (2014) The economic resource scarcity potential
 (ESP) for evaluating resource use based on life cycle assessment. Int J Life Cycle Assess
 19:601–610. doi: 10.1007/s11367-013-0666-1
- Sonderegger T, Dewulf J, Fantke P, et al (2017) Towards harmonizing natural resources as an area of
 protection in life cycle impact assessment. Int J Life Cycle Assess 22:1912–1927. doi:
 10.1007/s11367-017-1297-8
- Sonnemann G, Gemechu ED, Adibi N, et al (2015) From a critical review to a conceptual framework
 for integrating the criticality of resources into Life Cycle Sustainability Assessment. J Clean Prod
 94:20–34. doi: 10.1016/j.jclepro.2015.01.082
- Steen B (1999) A systematic approach to environmental priority strategies in product development.
 CPM Centre for Environmental Assessment of Products and Material Systems
- Steen B (2016) Calculation of Monetary Values of Environmental Impacts from Emissions and
 Resource Use The Case of Using the EPS 2015d Impact Assessment Method. J Sustain Dev
 9:15. doi: 10.5539/jsd.v9n6p15
- Steen BA (2006) Abiotic Resource Depletion. Different perceptions of the problem with mineral
 deposits. Int J Life Cycle Assess 11:49–54. doi: 10.1065/lca2006.04.011
- Steinmann ZJN, Schipper AM, Hauck M, et al (2017) Resource Footprints are Good Proxies of
 Environmental Damage. Environ Sci Technol 51:6360–6366. doi: 10.1021/acs.est.7b00698
- 822 Stewart M, Weidema B (2005) A consistent framework for assessing the impacts from resource use: A 823 functionality. J Life Assess 10:240-247. focus on resource Int Cycle doi: 824 10.1065/lca2004.10.184
- Swart P, Alvarenga RAF, Dewulf J (2015) Abiotic Resource Use. In: Life Cycle Impact Assessment.
 Springer, Dordrecht, pp 247–271
- Swart P, Dewulf J (2013) Quantifying the impacts of primary metal resource use in life cycle
 assessment based on recent mining data. Resour Conserv Recycl 73:180–187. doi:
 10.1016/j.resconrec.2013.02.007
- 830 Szargut J, Morris DR, R. SF (1988) Exergy analysis of thermal, chemical and metallurgical processes.
 831 Hemisphere Publishing, New York
- Taelman SE, De Meester S, Schaubroeck T, et al (2014) Accounting for the occupation of the marine
 environment as a natural resource in life cycle assessment: An exergy based approach. Resour

- 834 Conserv Recycl 91:1–10. doi: 10.1016/j.resconrec.2014.07.009
- Tilton JE, Crowson PCF, DeYoung JH, et al (2018) Public policy and future mineral supplies. Resour
 Policy 57:55–60. doi: 10.1016/j.resourpol.2018.01.006
- 837 USGS (2010) Mineral Commodity Summaries 2010. US Geol Surv 196. doi:
 838 http://dx.doi.org/10.3133/70140094
- Valero A, Valero A (2015) Thermodynamic Rarity and the Loss of Mineral Wealth. Energies 8:821–
 840 836. doi: 10.3390/en8020821
- Valero A, Valero A, Stanek W (2018) Assessing the exergy degradation of the natural capital: From
 Szargut's updated reference environment to the new thermoecological-cost methodology. Energy
 163:1140–1149. doi: 10.1016/j.energy.2018.08.091
- van Oers L, de Koning A, Guinée JB, et al (2002a) Abiotic resource depletion in LCA. Improving
 characterisation factors for abiotic resource depletion as recommended in the new Dutch LCA
 Handbook. Road and Hydraulic Engineering Institute of the Dutch Ministry of Transport
- van Oers L, Guinée J (2016) The Abiotic Depletion Potential: Background, Updates, and Future.
 Resources 5:16. doi: 10.3390/resources5010016
- van Oers L, Koning A De, Guinée JB, et al (2002b) Abiotic resource depletion in LCA. Improving
 characterisation factors for abiotic resource depletion as recommended in the new Dutch LCA
 Handbook. Road and Hydraulic Engineering Institute of the Dutch Ministry of Transport
- Vieira MDM (2018) Fossil and mineral resource scarcity in Life Cycle Assessment. Radboud
 University Nijmegen, the Netherlands
- Vieira MDM, Goedkoop MJ, Storm P, Huijbregts MAJ (2012) Ore grade decrease as life cycle impact
 indicator for metal scarcity: The case of copper. Environ Sci Technol 46:12772–12778. doi:
 10.1021/es302721t
- Vieira MDM, Ponsioen TC, Goedkoop MJ, Huijbregts MAJ (2016a) Surplus Ore Potential as a
 Scarcity Indicator for Resource Extraction. J Ind Ecol. doi: 10.1111/jiec.12444
- Vieira MDM, Ponsioen TC, Goedkoop MJ, Huijbregts MAJ (2016b) Surplus Cost Potential as a Life
 Cycle Impact Indicator for Metal Extraction. Resources 5:2. doi: 10.3390/resources5010002
- Weidema BP, Hauschild MZ, Jolliet O (2007) Preparing characterisation methods for endpoint impact
 assessment. Available from lca-net.com/files/Stepwise2006v1.5.3.zip
- Wenzel H, Hauschild MZ, Alting L (1997) Environmental Assessment of Products Volume 1
 Methodology, Tools and Case Studies in Product Development. Chapman & Hall
- West J (2011) Decreasing Metal Ore Grades: Are They Really Being Driven by the Depletion of High 28

866	Grade Deposits? J Ind Ecol 15:165–168. doi: 10.1111/j.1530-9290.2011.00334.x								
867	World	Bank	(2018)	The	Worldwide	Governance	Indicators.		
868	http://info.worldbank.org/governance/wgi/index.aspx#home								